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THE ESTIMATION OF MONTHLY RAINFALL FROM SATELLITE DATA

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ABSTRACT

The global distribution of precipitation is an outstanding example of a pattern whose form cannot be deduced very satisfactorily from conventional observational data. Many investigations of the global hydrological cycle across real periods of time are based on broadly generalized assumptions concerning rainfall patterns, especially over the world's oceans. This paper explores the feasibility of employing observational data from meteorological satellites to yield more acceptable maps of rainfall across periods of 1 mo and upward than is possible using conventional surface measurements, whose distributions are less uniform, and whose derivations are more heterogeneous, than the satellite data coverage. The central problem is related to the fact that satellites cannot measure rainfall directly, and the solution of this problem necessitates the construction of a rainfall coefficient equation to be evaluated from nephanalysis indications of cloud cover. Evaluated coefficients for the months of March, April, May, and June 1966 were plotted against the corresponding rainfall recordings from a selected scatter of surface stations in the Australian region, and a best fit regression line was computed to relate the two sets of values. The regression equation was used subsequently in the compilation of a map of the estimated precipitation field for July 1966 covering Australia and adjacent areas. Finally, the implications, and some potential applications, of the method are discussed, and suggestions are made concerning its possible further development in association with satellite photographs and computer techniques of data processing and data analysis.

1. INTRODUCTION, THE NATURE OF THE PROBLEM

Along with the rapid development in recent years of high-speed electronic computers, there has been a growing interest in mathematical model building of the atmosphere, with a view to an elucidation of patterns and processes that have a bearing upon the applied meteorological problems of long-range weather forecasting. Most progress seems to have been made where relatively simple atmospheric variables are involved, for example, temperature, pressure, and mean wind fields. (See, inter alia, Adem 1964 and 1967.) Less progress has been made with certain other elements of weather and climate, among which, precipitation is, perhaps, the most outstanding example.

Miyakoda et al. (1969), after attempting extended atmospheric predictions with a nine-level hemispheric model, concluded that ". . . it is almost impossible at present to collect worldwide observations of precipitation, especially across the oceans." This fact causes the global distributions of precipitation to be especially difficult to predict: until global patterns of precipitation can be documented better than the present inadequate network of conventional weather stations permits, predicted precipitation patterns cannot be expected to bear more than a very general resemblance to reality.

However, Miyakoda continued by saying that "Televised cloud pictures of recent meteorological satellites could provide the basis for estimating the distribution of the global weather." The primary aim of the present paper is to propose a type of methodology whereby meteorological satellite data, though not indicating precipitation totals directly, may be processed to yield maps of rainfall distributions covering periods of more than 1 mo more acceptably than is possible using the incomplete and less homogeneous indications derived from surface rainfall stations, whose individual aspects, altitudes, and exposures often bear heavily upon their records.

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2. METHODOLOGY, ESTIMATING RAINFALL TOTALS FROM SATELLITE NEPHANALYSES

Since the inauguration of the fully operational ESSA weather satellite system in February 1966, cloud charts or *nephanalyses* have been prepared daily in the U.S. Weather Bureau to cover about five-sixths of the earth's surface once daily, a much higher routine coverage than had been achieved by similar means theretofore. Conventionally, nephanalyses portray the rich photographic data (which, like all aerial photographic data are nonselective above the resolution of the equipment system) in a generalized way (Barrett 1967, chapter 3). Cloudiness is portrayed basically in terms of:

1) type, including cumulonimbus, cumuliform, stratocumuliform, stratiform, and cirriform cloud categories, and

2) percentage overcast, including "Open" ($<$20 percent cloud cover), "Mostly Open" (20–50 percent), "Mostly Covered" (50–80 percent), and "Covered" ($>$80 percent).

Comparisons between contemporaneous nephanalyses and surface overcast observations have shown that the four categories listed under 2) above can be represented satisfactorily by their median values for purposes of quantifying mean cloud cover over periods of 2 weeks and longer (Barrett 1968, chapter 5). Hence, "Open" may be taken to indicate a 10 percent cloud cover, "Mostly Open" 35 percent, "Mostly Covered" 65 percent, and "Covered"

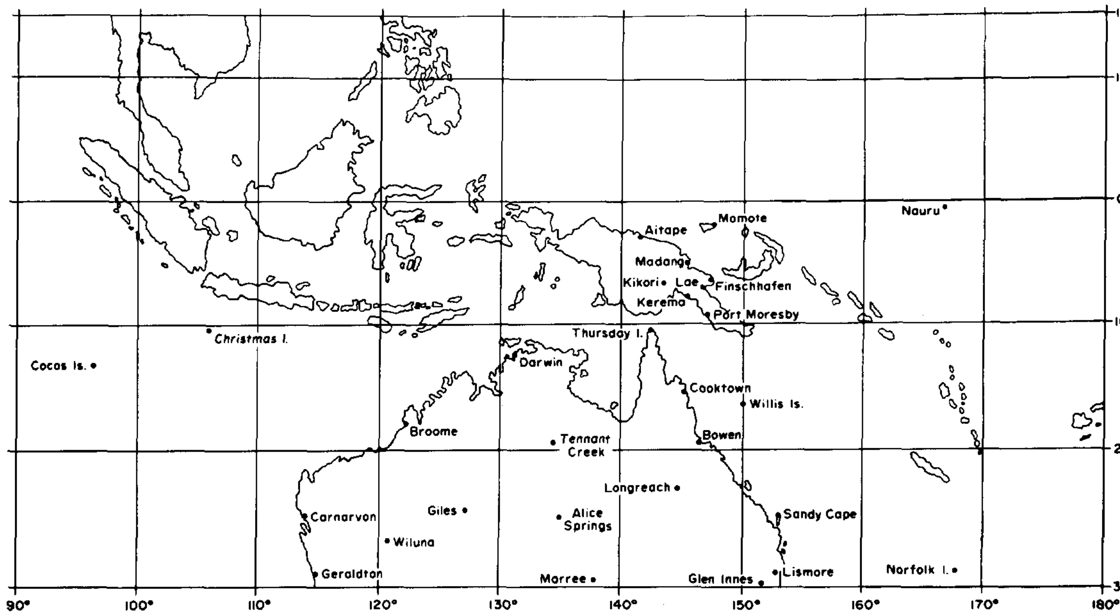

FIGURE 1.—Selected rainfall stations in the Australian region.

90 percent. There is a tendency for cloud cover to be slightly overestimated at the higher end, but the discrepancies, on the average, are very small (1–2 percent) in the British region.

In the present investigatory study, ESSA nephanalyses are the only satellite data employed, solely because of the relative ease with which they can be scanned for cloud types and percentages of overcast. Since nephanalyses are very generalized representations of satellite photographic data, it is probable that better results in this context could have been derived from a joint nephanalysis/photographic technique, but for the purposes of a preliminary investigation, the cloud charts were used alone. Further work, once the acceptability of the basic technique is established, should involve the more detailed photographs to give more accurate results. Probably, more problems were encountered through the use of nephanalyses alone, but it seemed that these could be resolved more rapidly within the general methodological framework than the alternative, larger problems arising from the handling and use of photographs also.

The methodology includes two major parts, namely:

1) *The design of an equation to yield, for a given point over a chosen period of time, a rainfall coefficient evaluated from features of the cloud field; and*

2) *The transformation of the coefficient into a rainfall estimate, based on empirical relationships between corresponding coefficient values and rainfall recordings for selected weather stations.* (See fig. 1.) It is necessary to describe these two stages in further detail.

Stage 1) In the design of a *rainfall coefficient*, the following criteria were involved:

a) The nephanalysis-derived mean monthly cloud cover percentage. This weighting factor is a gross measure of the persistence or mobility of (rain) clouds.

b) The probabilities of falls of rain from the nephanalysis cloud types. Since no objective studies known to the present author have related rainfall probabilities to these major cloud categories, a scale of probabilities had to be drawn up to quantify scientific intuition. The scale is listed in table 1 as column 2.

c) The likely intensities of rainfalls from different categories of cloudiness. Values were ascribed as in b), and for the same reasons. The relative rainfall intensities that were adopted are shown in table 1, column 3. In the evaluation of equation (1) below, an occurrence of cumulonimbus cloud, therefore, lends a contribution of 0.72 toward K_r, stratiform cloud 0.25, cumuliform cloud 0.20, and stratocumuliform and cirriform cloud 0.01 apiece.

The possible effects of altitude and local topography upon precipitation patterns were ignored. The first effect is probably covered, in part at least, by the higher incidence of cloudiness in mountainous regions, and, therefore, by a higher weighting factor under i) above. The second is probably less well covered by that factor, and it became apparent in the Papua-New Guinea region that the final rainfall estimates were usually too low on the windward side of this very mountainous island, and too high on the leeward. Across ocean areas, however, systematic anomalies of similar kinds are highly unlikely.

The basic rainfall coefficient equation can be written as

$$\frac{K_r = C\sum(Mp_1i_1c_1 + Np_2i_2c_2 \ldots Rp_6i_6c_6)}{100} \tag{1}$$

where C is the mean monthly percentage of cloud cover; Σ is the sum of available daily nephanalysis cloud data in one calendar month; $p_1 \ldots p_6$ are the assigned probabilities of rainfall from each type of cloudiness; $i_1 \ldots i_6$ are the assigned intensities of rainfall; $c_1 \ldots c_6$

TABLE 1.—*Rainfall probabilities and intensities as related to states of the sky*

1 States of the sky (nephanalysis cloud categories)	2 Assigned probabilities of rainfall (relative scale range 0–1.00)	3 Assigned intensities of rainfall (relative scale range 0–1.00)
Cumulonimbus	0.90	0.80
Stratiform	.50	.50
Cumuliform	.10	.20
Stratocumuliform	.10	.01
Cirriform	.10	.01
Clear skies	—	—

are the six states of the sky listed in table 1, column 1; and M . . . R are the numbers of occurrences of the six states of the sky.

One last point must be made with reference to the structuring of the coefficients, this relating to the appearance on nephanalyses of "synoptically significant cloud systems." These systems are associated with large atmospheric organizations such as vortices, frontal zones, etc. From these, heavier and more sustained rainfalls are expected than from more localized and less-well organized areas of clouds. Where such synoptically significant systems occurred, therefore, the indices for cumulonimbus and stritiform clouds (the dominant rain clouds involved) were weighted by a factor of 4, a value that seemed reasonable in view of the principles involved. The acceptability of this, and the other basic assumptions, can be attested only in practice. No separate factor was included in connection with altitude, since it was argued that the enhanced cloudiness along zones of orographic uplift would, of itself, yield higher precipitation estimates.

Two main practical problems remained to be resolved before the equation could be evaluated for any location. First, nephanalysis data deficiencies had to be made good. The commonest deficiency was an absence of data for a particular date. All the available ESSA nephanalyses for a given month were used for coefficient evaluation, and, where necessary, the resulting values were adjusted upward to represent the complete month. Since in some cases nephanalyses were missing for up to 6 days in any one month, this deficiency was probably one of the major sources of error leading to a rather wide scatter of points plotted in figure 2, but its effect upon the alinement of the regression curve is likely to be small, since some coefficients must have been overevaluated, and some underevaluated as a result of the proportional adjustments.

The second practical problem related to the fact that areas of cloudiness on nephanalyses are rarely annotated for single cloud categories. Much more frequently, an area of cloud is shown to include two or more different types of clouds. It was decided to accept the most active precipitation cloud category within each cloud mass at each key location for the purpose of coefficient evaluation, unless the most active precipitation cloud was shown to be "scattered" in its distribution. Hence, for example, a mass

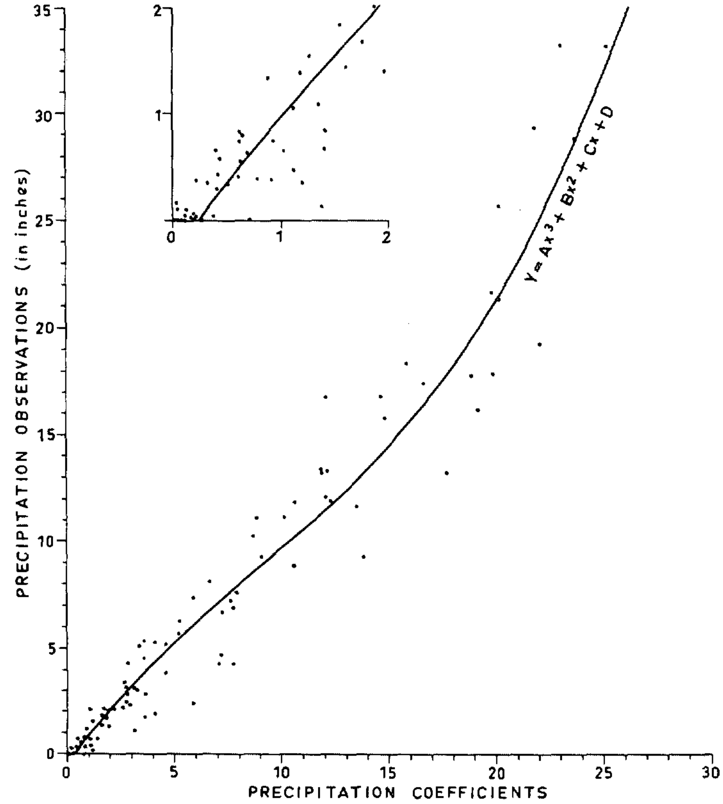

FIGURE 2.—Evaluated rainfall coefficients for rainfall stations portrayed in figure 1, plotted against actual rainfall recordings for the months of March–June 1966. The best fit computer curve is also indicated.

shown to contain cumuliform, cumulonimbus, and cirriform clouds was accepted as an area of cumulonimbus rainfall activity, and a mass containing scattered cumulonimbus, cumuliform, and cirriform clouds was classed an area of cumuliform rainfall.

Stage 2) The transformation of each evaluated rainfall coefficient into a *rainfall estimate* (in inches) is the most critical single step in the entire methodology. This was accomplished by selecting a number of rainfall stations reporting monthly data to the *Australian Monthly Climatological Summary of Surface Data* (Australian Bureau of Meteorology 1966) and plotting the corresponding coefficient values against the instrumental recordings for each of the 29 selected stations across the months of March, April, May, and June 1966. Figure 1 shows the rainfall stations employed for this purpose, and figure 2 displays the results. The stations were selected to give a good range of values in figure 2, *not* to influence the shape of the eventual best fit computer curve—the form of the curve mattered little so long as it was statistically sound.

Two techniques were tested on the two sets of data in the search for a best fit curve. First, a relaxation method was used to fit two types of curve to the observations, but the subsequent measure of error residual, while reduced by the process of curve fitting, failed to fall below that produced by the second technique, which was that

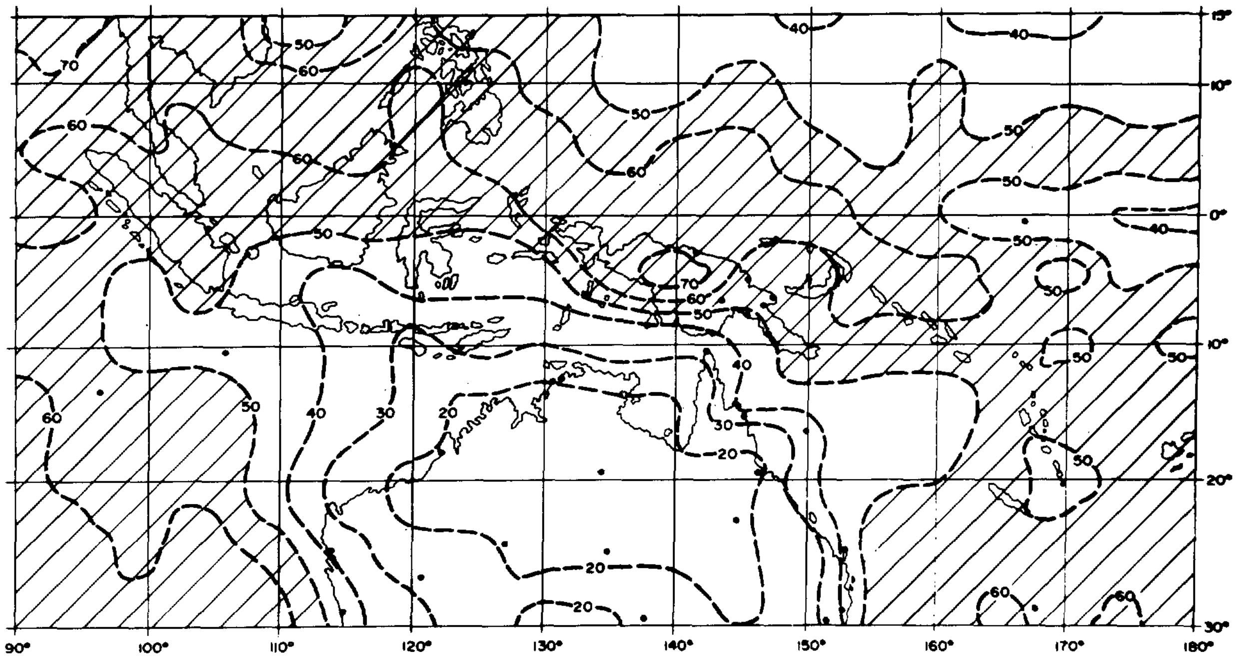

FIGURE 3.—Average cloudiness, July 1966, derived from daily nephanalysis evidence across a 5° grid network of latitude and longitude.

of standard linear regression. In this second approach, a series of polynomial equations were developed with evaluated rainfall coefficients as the independent variables and recorded rainfalls as the dependent variables. The 3d degree, or cubic polynomial, proved the best fit, with a multiple correlation of 95.27 percent and coefficients significant at 5 percent and 1 percent levels.

The general form of the polynomial finally employed may be represented by

$$y = Ax^3 + Bx^2 + Cx + D, \tag{2}$$

and the specific form was

$$y = 0.00200x^3 - 0.05108x^2 + 1.30107x - 0.32750. \tag{3}$$

A table of relationships was then computed, listing *rainfall estimates* at intervals of 0.01 in. for rainfall coefficients evaluated within the range from $x = 0.25$ in. (where $y \doteq 0$) to $x = 30.00$ in. (which experience deemed sufficiently high for a 1-mo investigation of the Australian region). Evaluated coefficients of ≤ 0.25 in. were taken to indicate a zero rainfall estimate.

The table was used subsequently to derive estimates of rainfall from the nephanalysis-based rainfall coefficients evaluated for every 5° grid intersection of latitude and longitude from 90° to 180° E., and from 15° N. to 30° S. The estimates were plotted in map form, and isohyetal patterns interpolated as shown in figure 4. Figure 3, portraying average cloudiness for the same trial month of July 1966, was compiled as a by-product of the method for rainfall estimation, and the two maps should be studied together.

The general soundness of the whole methodology was then tested by the compilation of a contingency table (fig. 5) relating July 1966 rainfall recorded at the selected stations to values derived from the patterns portrayed in figure 4. Despite the coarseness of the network that had been employed, yielding a generalized "precipitation field" pattern rather than a detailed rainfall distribution, 17 of the 29 stations for which data were evaluated fell into the correct categories, and 26 were either in the correct categories or only one removed therefrom. This seemed to be a most encouraging result in view of all the assumptions that had to be made initially, the various data deficiencies, and the coarse grid network through which some of the localized embroideries of the precipitation pattern must have escaped unnoticed.

3. DISCUSSION OF RESULTS

The circulation pattern in the Australian region is dominated in the month of July by anticyclonic conditions over the center and north of the continent, with low pressure extending southeastward from Asia across the tropical Pacific Ocean. Figure 3, portraying mean cloudiness in July 1966, conforms well with the normal circulation pattern in that month. Very low cloud cover values (<20 percent) spread across much of northern and central Australia, while (<50 percent) cloud cover extends northwestward in sympathy with the dry southeast monsoon winds. Higher incidences of cloud cover closely approach the east and west Australian shores, although the patterns are notably more complex to the east than to the west. A belt of especially heavy cloud cover extends east-

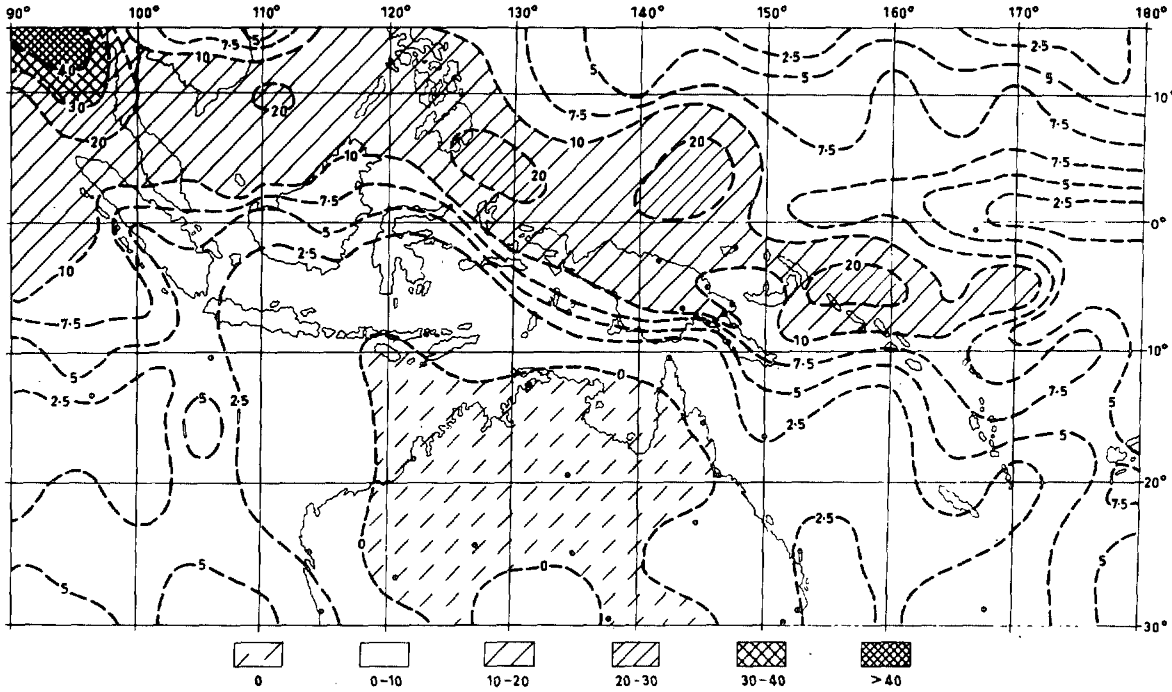

FIGURE 4.—Estimated precipitation field, July 1966, derived from daily nephanalysis evidence across a 5° grid network of latitude and longitude, and the computed relationships between evaluated rainfall coefficients and recorded rainfall.

southeast from Southeast Asia across Melanesia. From about 135° E. eastward, the strong cloudiness may be related to the intertropical convergence. The clearance about the Equator from 160° E. to 180° E. is reminiscent of patterns illustrated by multiple-exposure satellite photographs described by Kornfield et al. (1967) and is a further pointer to a more complex circulation pattern in low latitudes than that deduced in presatellite days.

Figure 4, the map drawn from rainfall estimates, contains some interesting similarities and dissimilarities compared with figure 5. The highest precipitation estimates are in the extreme northwest, doubtless stimulated by the convergence of the wet southwest trades in Southeast Asia. From the area of highest precipitation, the estimates suggest a belt of very wet conditions extending east-southeast, its axis lying a little to the north of New Guinea. These high rainfall zones coincide quite closely with the zone of maximum cloudiness displayed in figure 5. Across much of central and northern Australia, minimal precipitation totals were estimated. In the sea areas to the east and west of Australia, the estimated isohyets cross obliquely the lines of equal cloud cover, precipitation probably increasing southward from the centers of the oceanic anticyclones. Perhaps the most prominent feature of all is the very steep rainfall gradient estimated to stretch generally east-west through southern Papua-New Guinea and to the north of the Australian Continent. Indeed, the gradient is almost certainly steeper in some areas than this rather generalized map suggests, since the rainfall estimates for stations in southern Papua-New Guinea were generally too high and those for two north coast stations were too low. It seems that, while the equations listed earlier describe suprisingly well the rainfall distributions in most topographic regions, some further factors need to be included for application to regions of very abrupt relief. Probably the inclusion of a latitudinal factor might be necessitated also, if the approach were to be applied to regions with a considerable latitudinal spread.

The key question that underlies the acceptability of the approach as a whole is clearly concerned with the extent to which precipitation processes over maritime surfaces resemble those over land. Because of the sparseness of truly maritime data in the Australian region, and the absence, yet again, of earlier definitive research on the subject, it has had to be assumed that the processes over land and sea surfaces are similar. Indeed, it can be argued that precipitation patterns over sea surfaces should be more easily estimated than those over land since the patterns are probably prompted more by purely atmospheric factors and less by complex topographic variations, yielding *instantaneous* distributions of precipitation activity that are more random than those over land, but *average* distributions that are less complex. These possibilities are, however, difficult to substantiate. Malkus and Ronne (1960) pointed out that, within the tropical ocean areas, the major fraction of monthly precipitation falls on a very few days, and is almost entirely concentrated in major disturbances on the synoptic scale. This makes the problem of comparing satellite precipitation estimates with oceanic rainfall recordings all the more difficult, since even

RECORDED PRECIPITATION (in inches)	ESTIMATED PRECIPITATION (in inches)							
	0	0–2·5	2·5–5	5–7·5	7·5–10	10 – 20	20 – 30	TOTALS
0	5							5
0–2·5	2	7	3	1				13
2·5–5			3					3
5–7·5			1	1		1		3
7·5–10			1					1
10–20					1	1		2
20–30						2		2
TOTALS	7	7	8	2	1	4	0	29

Figure 5.—Contingency table for the rainfall stations mapped in figure 1 to test the accuracy of the isohyetal pattern in figure 4.

the humblest islands and atolls within the Tropics tend to be "hot spots" for convective activity, so that these localities may not be very representative, in terms of monthly rainfall totals, of the oceans in which they stand

Notwithstanding these theoretical problems, however, it seems that this method of rainfall estimation may be potentially better than any devised previously, since its basis is one of real, and uniform, observational data. The first stage in the search for an even better estimate must involve satellite photographs as well as nephanalyses to eliminate some of the contamination caused by the overgeneralizations of cloud categories and their distributions on the cloud charts. One practical problem that would have to be solved if a similar methodology were adapted for global scale precipitation field estimation concerns the time required to evaluate a 1-mo rainfall coefficient for each location—the coarse, 5°, grid network employed in this study was chosen partly because of the lengthy nature of the repetitive procedure when carried out mostly by hand. It seems that it would be worthwhile to investigate whether a similar method could be applied satisfactorily to nephanalysis and/or photographic data (preferably the latter alone) using multiple averaging of photographic brightness levels to estimate monthly cloud cover percentages, and the brightness levels on individual photographs for each day of the month to locate and identify different categories of cloudiness. It should not be impossible to construct a methodology whereby global rainfall patterns could be estimated by computers alone, yielding month-by-month patterns for incorporation into a wide variety of global atmospheric models. Perhaps the scheme could be dovetailed into the conventional rainfall data networks by compiling hybrid maps of the world, showing generalized patterns of recorded precipitation data over land areas and estimated patterns over the oceans.

Suffice it to say, in conclusion, that the pilot study described above appears to justify further investigations into the possibility of deriving acceptable estimates of rainfall distributions from weather satellite data. In detail, the satellite-derived patterns might well differ from those compiled from conventional sources, but rainfall is so sensitive to spatial variation on the local scale that a new, and independent, assessment of precipitation distribution might not come amiss, especially in meteorological and climatological studies at the mesoscales, synoptic scales, and global scales of inquiry.

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